The language of

Ecosystems
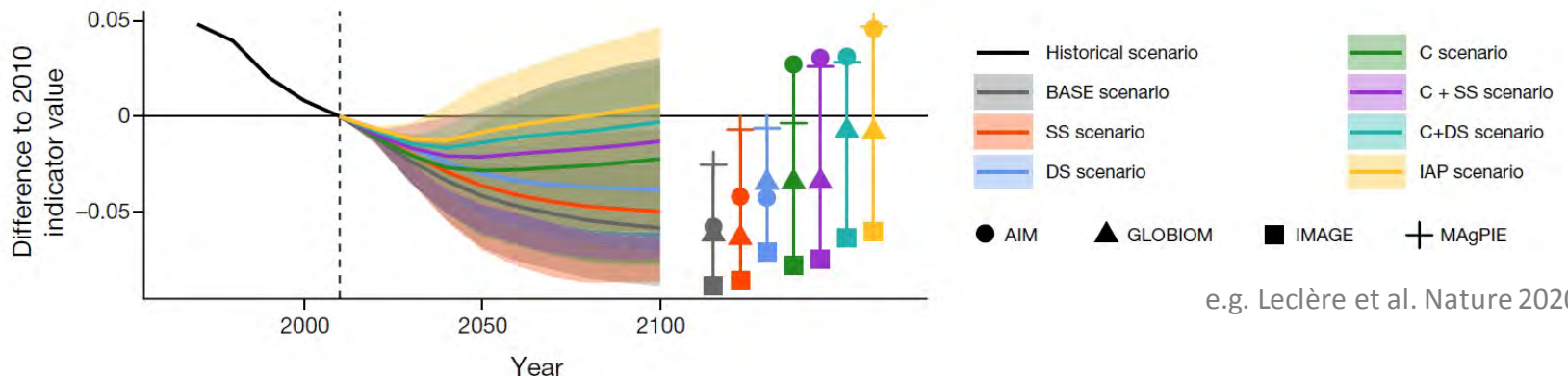
C. GAUCHEREL, WITH M. COSME, O. BERNARDOFF, C. CARPENTIER, F. POMMEREAU

Alert: Some species die!

e.g. the Quagga (South Africa, 1883) or

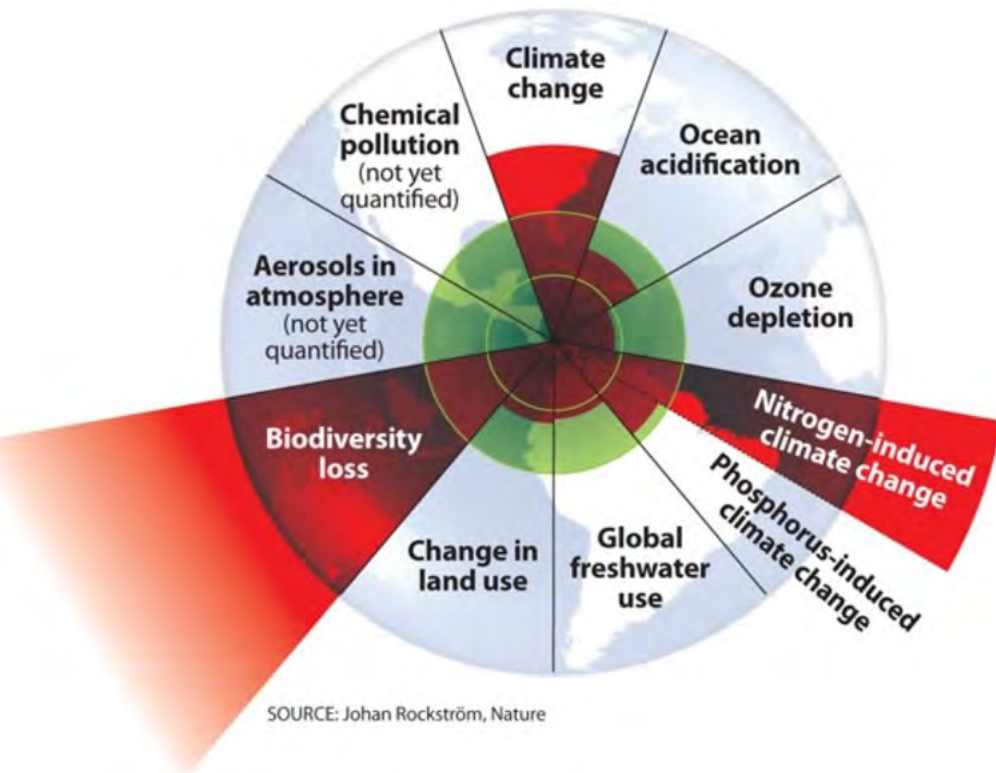The Round Island Burrowing Boa (near

Mauritius, 1975)

Extinctanimals.org

e.g. Leclère et al. Nature 2020

We loose species 100 to 10000 times more **rapidly** than the "natural" rate

Earth and Humans in danger
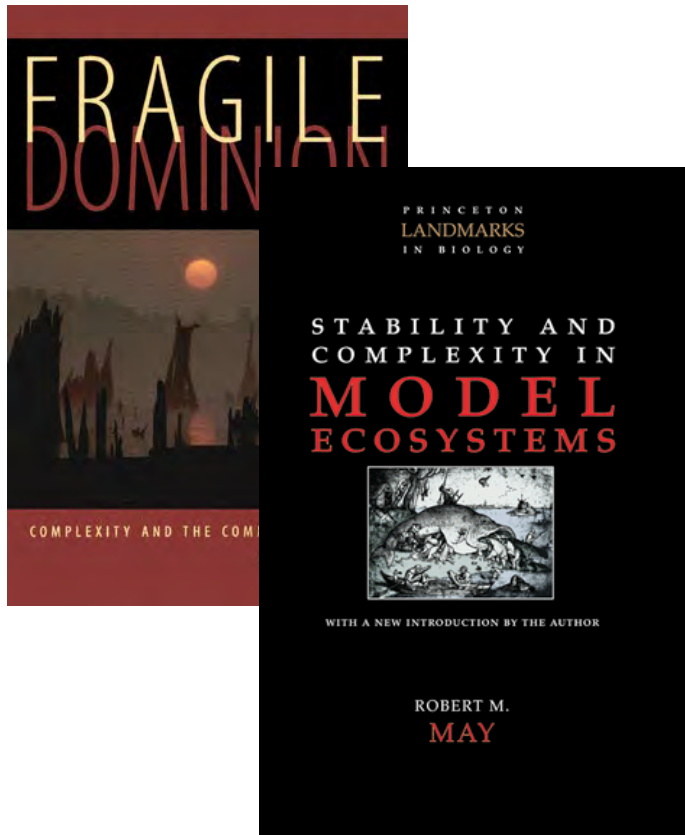

SOURCE: Johan Rockström, Nature

Sahel, Haïti 1999

Humans waste resources and strongly impact ecosystems which, in turn, impact them strongly!
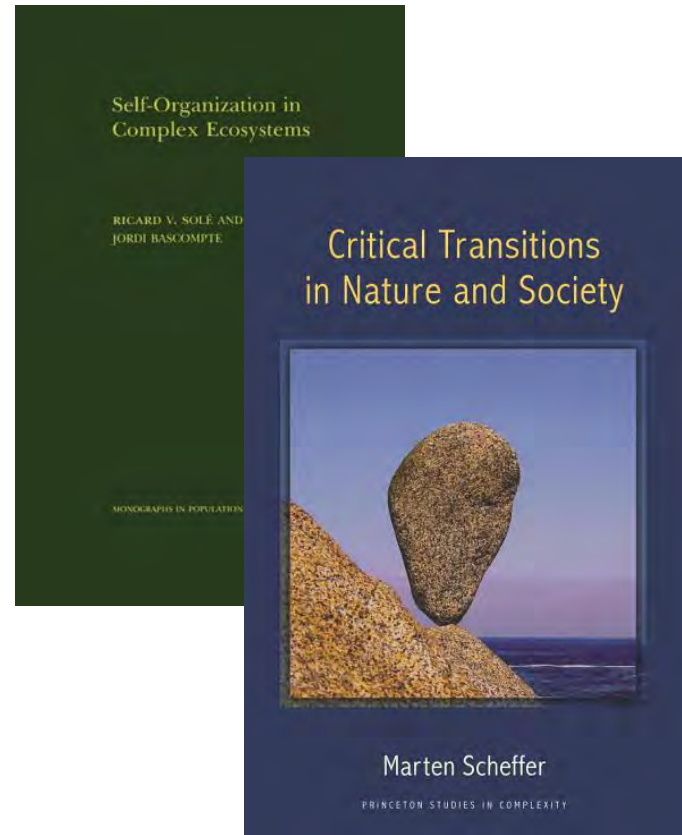
Many **threats on socio-ecosystems** and no option today to stop them

Are (socio-)ecosystems stable?

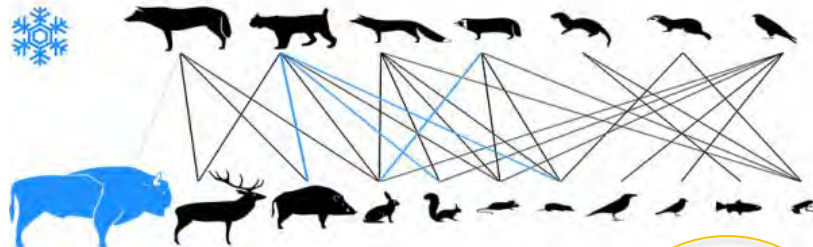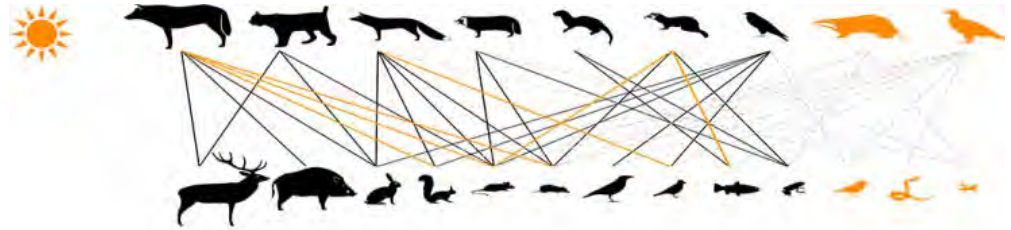S. Levin; R. May books

Looking for stability
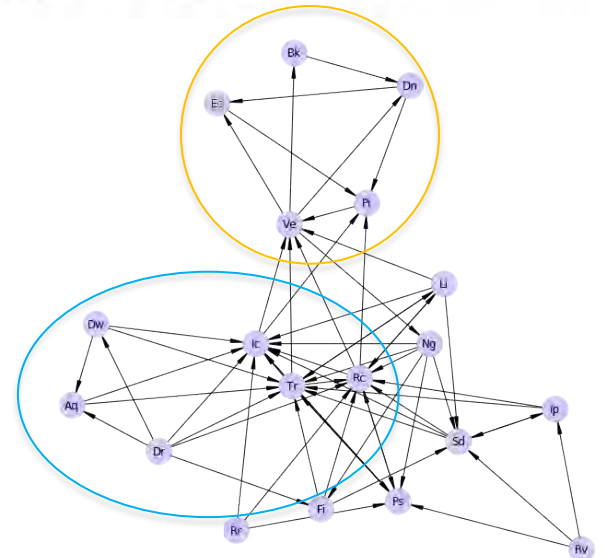
Solé & Bascompte; M. Scheffer books

Looking for instability

Ecologists still **debate** on (socio-)ecosystem dynamics

We do not know!

A social community may seems stable, while a species community not??

Several <u>flaws</u> so far: ecosystems considered without an ***integrated*** view, in the *short* term, as having a ***determinist*** and quantitative behaviour ...

Decompose the main question

Q2. which ecosystem **services** after strong perturbations of Camargue?
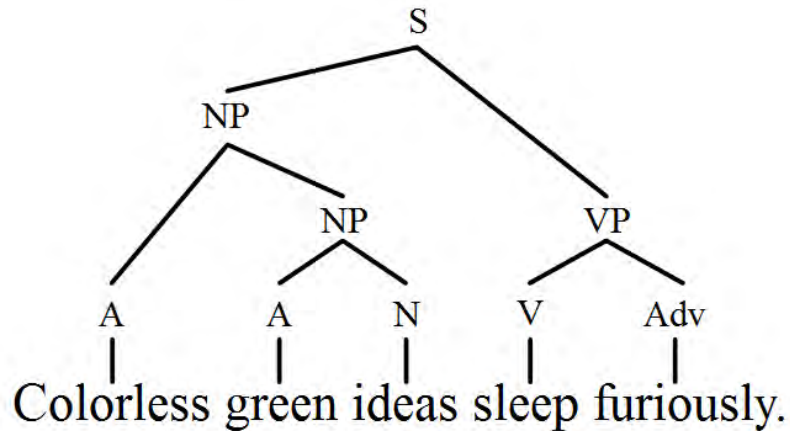

Q1. May agro-ecosystems **collapse**?

Q3. Are African landscapes **resilient** to a volcanic eruption?

Site-specific questions to **locally** understand Earth and Human dynamics

The language of ecosystems

Colorless green ideas sleep furiously.

Famous example of syntaxically correct

and semantically incorrect sentence

Chomsky 1957, 1995
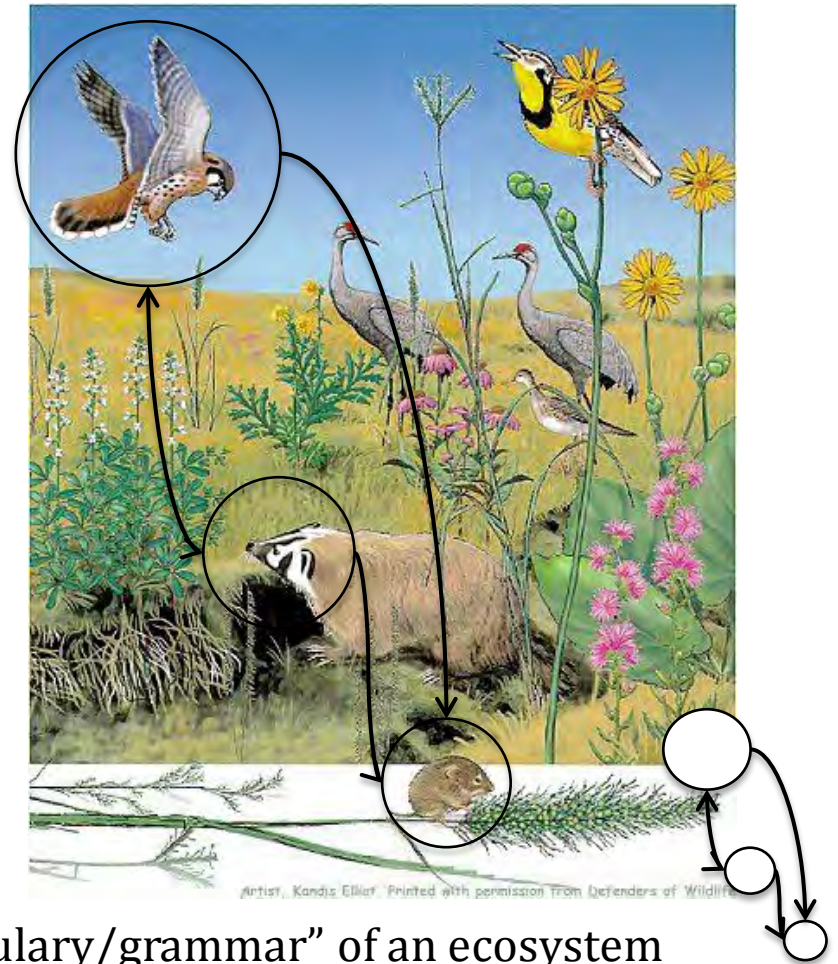
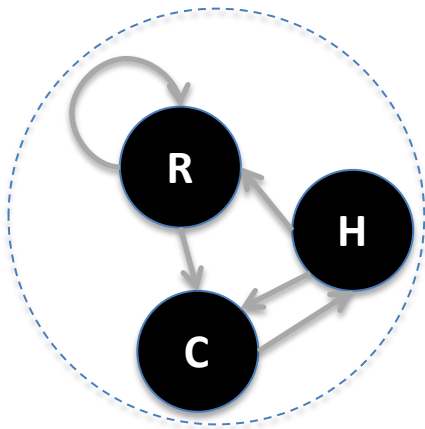Looking for the "vocabulary/grammar" of an ecosystem

Gaucherel 2019

Proposition to model ecosystems by a changing *graph* and its *language*

Q1. Agro-ecosystem dynamics

Q1. May agro-ecosystems collapse?

$+$ $=$ $?$

Ecosystem graph

| Rule:	Conditions → Realizations	Descriptions (qualitative + discrete-event)
R1:	*R+ → R-*	*Shift in dry season*
R2:	*R- → R+*	*Shift in rainy (R) season*
R3:	*R- → C-*	*Dry season may destroy crop fields (C)*
R4:	*R+, H+ → C+*	*Humans (H) plant crop fields (and feed on them)*
C1:	*C- → H-*	*Humans depend on crops (or die or move)*

Simplification and **formalization** of such a socio-ecosystem, to compute its responses to strong perturbations

Q1. Agro-ecosystem may collapse

The corresponding state-space and merged state space
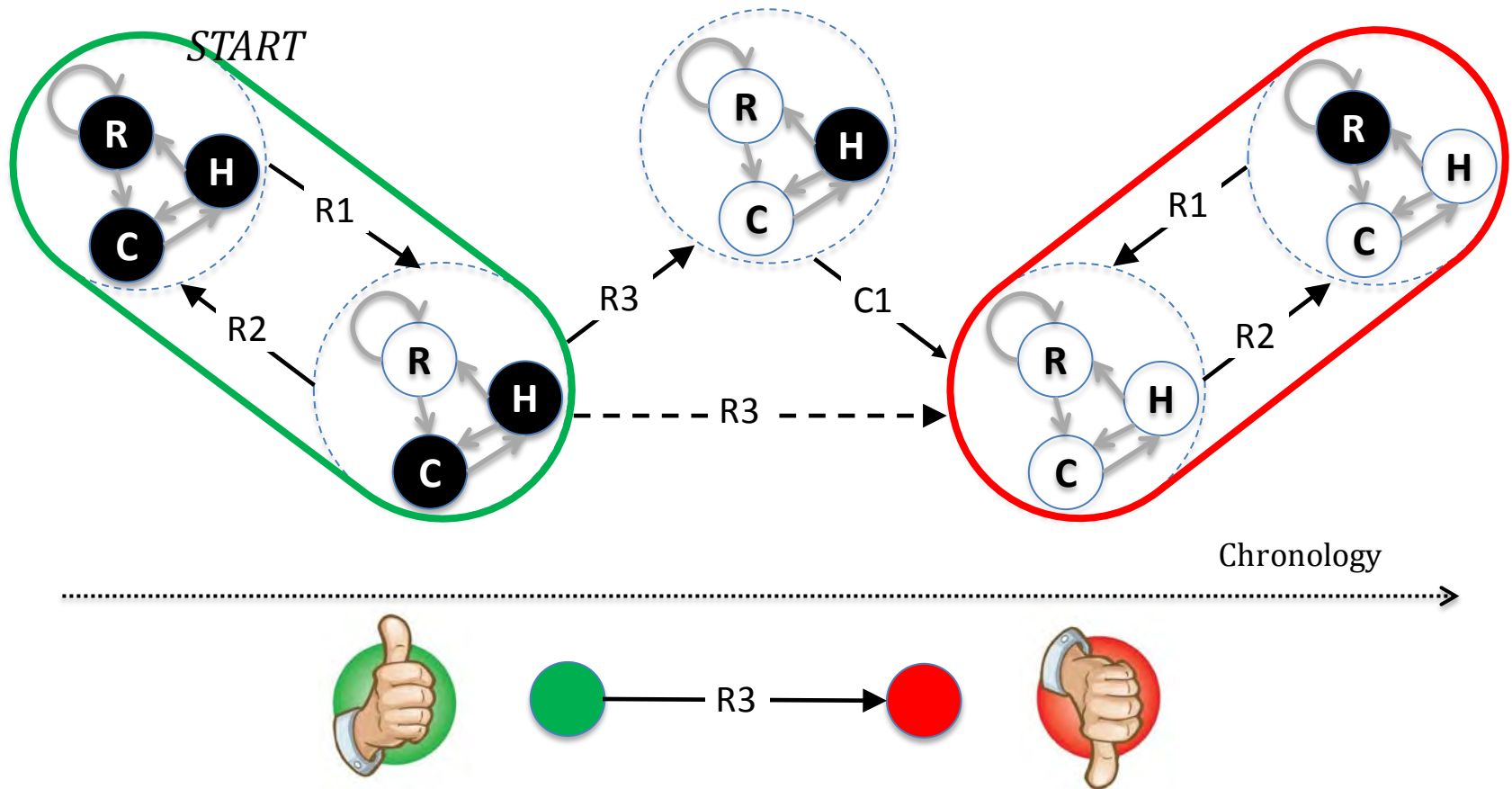
Conclusion that such agro-ecosystem may be stable **AND** instable

Gaucherel et al. 2019, Cosme et al. 2020

Q2. Ecosystem service bundle
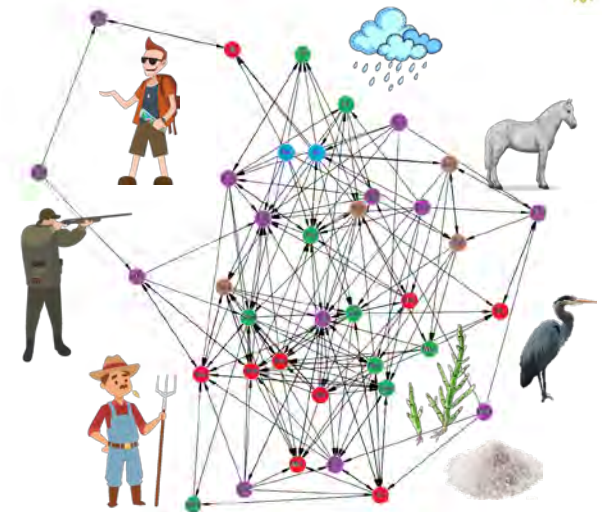

Q2. which ecosystem services after strong perturbations of Camargue?



```
                ...
Irr+ >> Swa+, SwH+, Lag+, Sal-, FiC+   # R3
Rai+ >> Swa+, Sal-   # R4
Irr- >> Swa-, SwH-, Lag-, Sal+, Ric-, San+, FiC-   # R5
Liv+ >> Gra-, San-, Ree-   # R17
Liv+, Env+ >> Gra+, San+, Ree+   # R18
SwH+, Sal- >> Ree+, San+   # R19
Swa+, Sal- >> Ree+, San+   # R20
Lag+, Sal-, Pol- >> Mac+   # R21
Ree+ >> Pol-, Brd+, Div+   # R24
Mac+ >> Pol-, FiL+, Div+   # R25
Ric+, OF- >> Pol+   # R52
Ric-, Cr- >> Pol-   # R53
Ric-, Cr+ >> Pol+   # R54
OF+ >> Pol-   # R55
Pol+ >> FiL-, FiC-, Brd-, Div-, Flm-, Mac-   # R56
Pol+, Ree-, Mac- >> Trt-   # R83
                ...
```

Much more **complicated/realistic** model (37 components and 119 processes)

Q2. A tiny service bundle

Which service bundle in case of strong perturbations (water + budget)?

State space

+ =

Ecosystem graph

Chronology
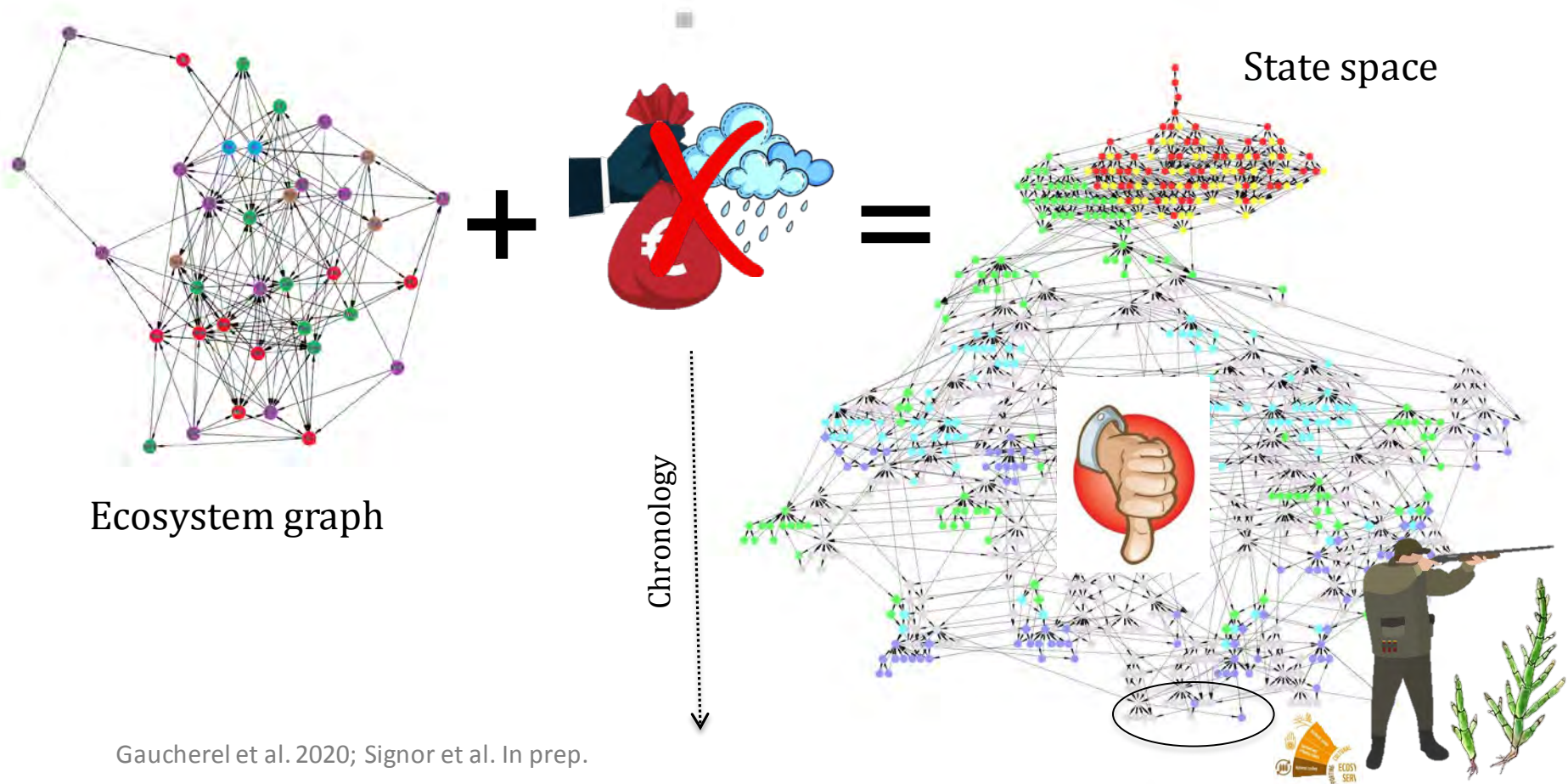
Most ecosystem services and vegetations (but not all) **disappear**

Q3. Ecosystem reconstruction

Q3. Are African savannas resilient to a volcanic eruption?
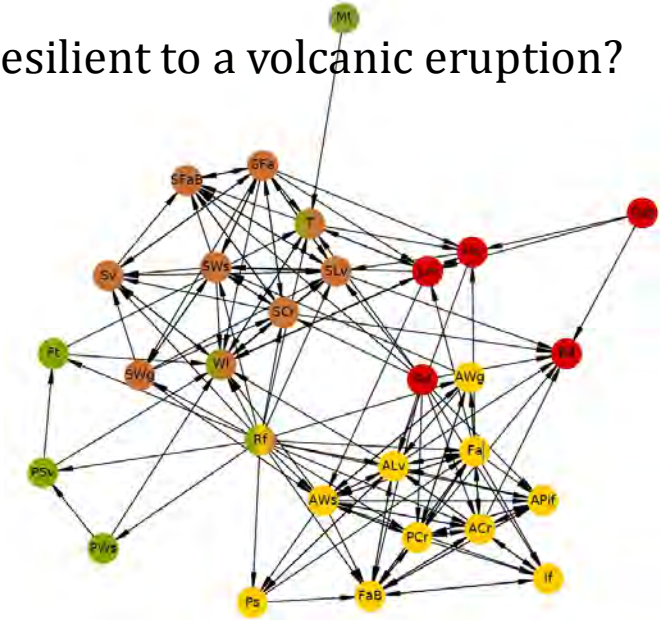
The Meru landscape + human activities

+ vegetations + wildlife …

	...	
R43:	El+, Lm- → Cr-	Without crop protection against elephants, this destroy crop fields
R44:	Ps+, Lm- → Cr-	Pests may destroy crops
R45:	Ag+, Lm- → El-	Without crop protection against elephants, farmers may kill elephants
R46:	Pa+ → Lm+	Pastoralism may induce/require management
R47:	Ag+ → Lm+	Agriculture may induce/require management
R48:	Gz+ → Lm+	Wildlife my require management
R49:	Bw+ → Lm+	Wildlife may require management
R50:	El+ → Lm+	Wildlife may require management
R51:	Ca+ → Lm+	Wildlife may require management
R52:	Lm+ → Bd-, Gd-	Authorities may eradicate livestock and wildlife disease
	...	

A highly contrasted model (29 components and 113 processes) with geology

Q3. The ecosystem regime shift

Blast eruption

Most human activities and vegetations would **recover** (with various trajectories)

Size classes

2	4	8	320	324	4032	4070	49616	51048	95584	97816
x16	x16	x8	x2	x2	x2	x2				

Cosme et al. Submitted
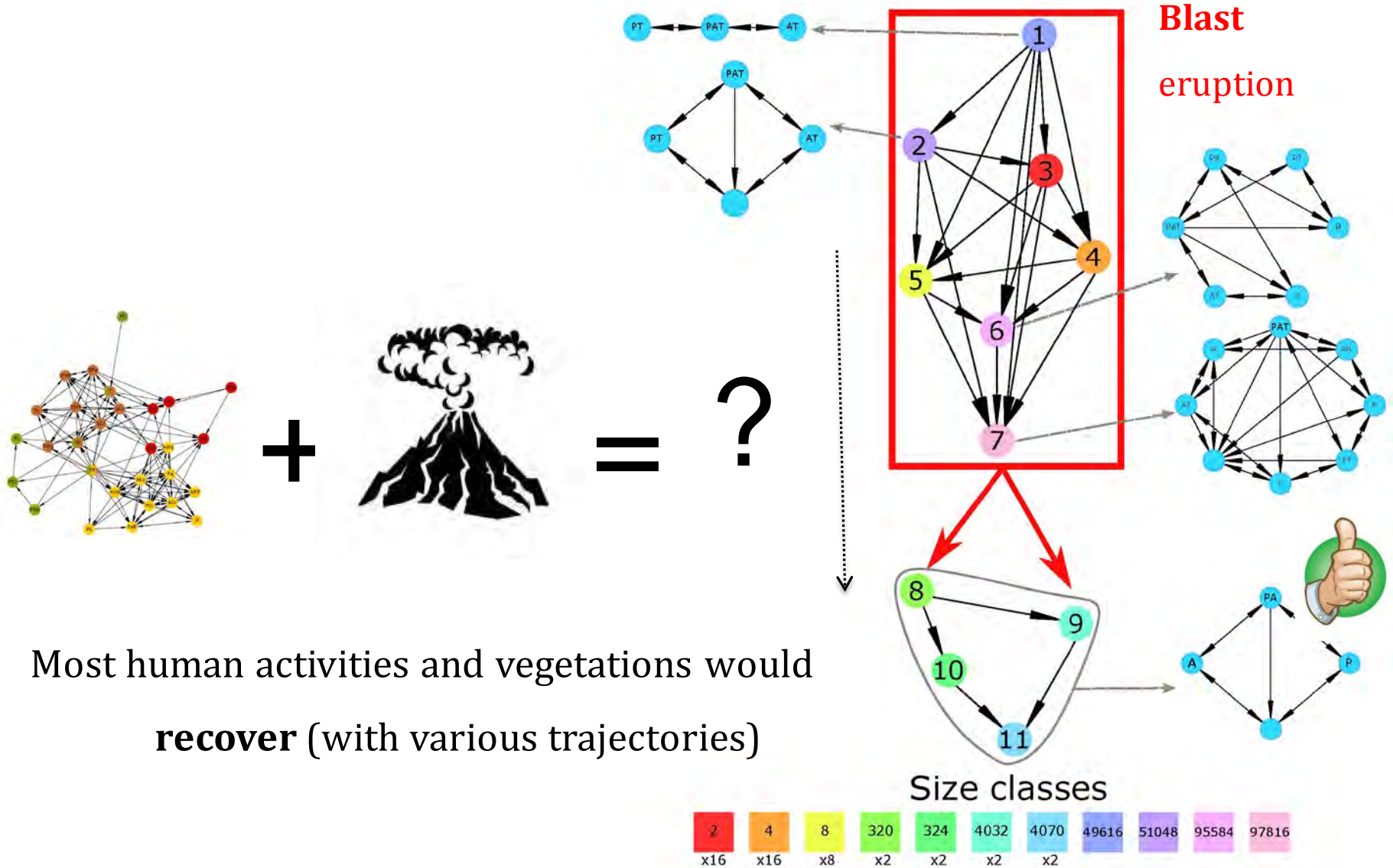
Local answers to local questions
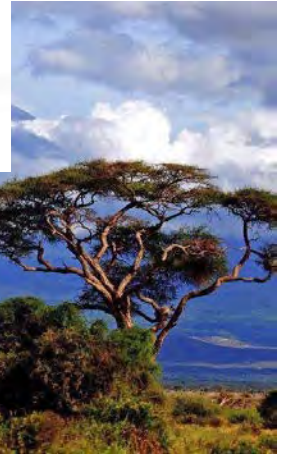
Appropriate models confirm that there exists a high **diversity** of dynamics,

and a diversity of answers about (socio-)ecosystem **stability**
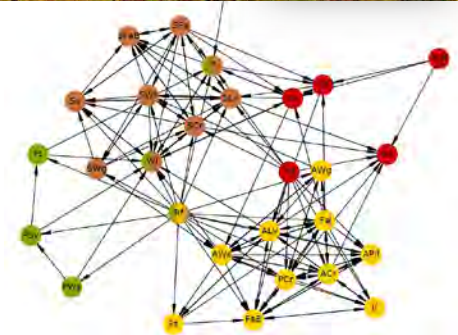
With the ecosystem languageS?
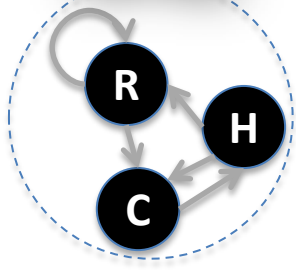
Invariants in
Syntax +
Semantics?

Gaucherel 2019

Each (socio-)ecosystem possesses its own **language**, but which one?

Earth and Humans in danger

On each site, locally ...

Gaucherel et al. 2020; Mao et al. 2020

Irr+ >> Swa+, SwH+, Lag+, Sal-, FiC+   # R3
Rai+ >> Swa+, Sal-   # R4
Irr- >> Swa-, SwH-, Lag-, Sal+, Ric-, San+, FiC-   # R5
Liv+ >> Gra-, San-, Ree-   # R17
Liv+, Env+ >> Gra+, San+, Ree+   # R18
SwH+, Sal- >> Ree+, San+   # R19
Swa+, Sal- >> Ree+   20
Lag+, Sal-, Pol-   21
Ree+ >> Pol-, Brd+   24
Mac+ >> Pol-, FiL+,   R25
Ric+, OF- >> Pol+
Ric-, Cr- >> Pol-
Ric-, Cr+ >
OF+
Pol+ >> FiL-,   Mac-   # R56
Pol+, Ree-, Ma

To help managing, we first have to *decode* the studied ecosystem

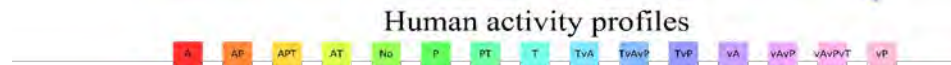language, and then to use it for **recommendations**

Chronology *(History since 2017)*

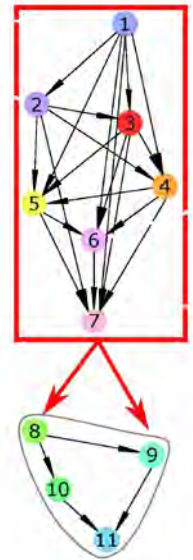From static to (equivalent) dynamical representations and syntheses
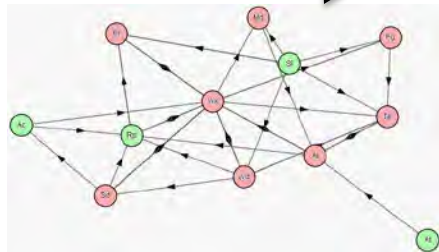
Ecosystem graph
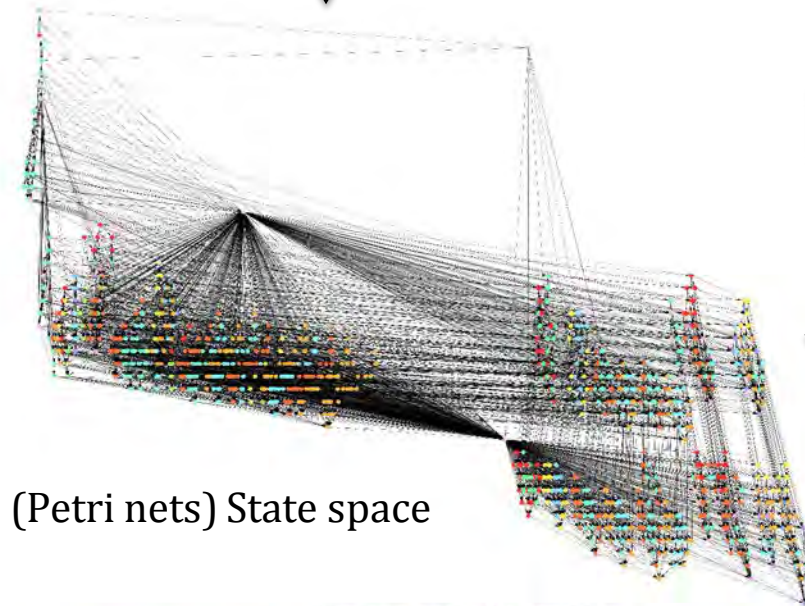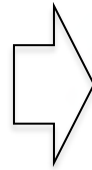
(Petri nets) State space

Human activity profiles

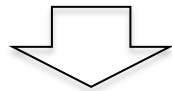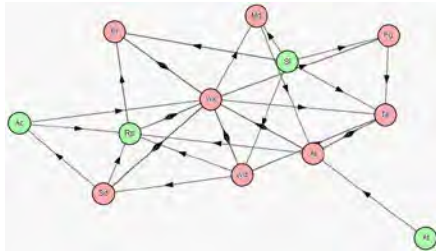Merged space

Gaucherel et al. 2020; Cosme et al. Submitted

Clear *limits* in computation, and challenges for analyzing the dynamics

Chronology *(since 2019)*
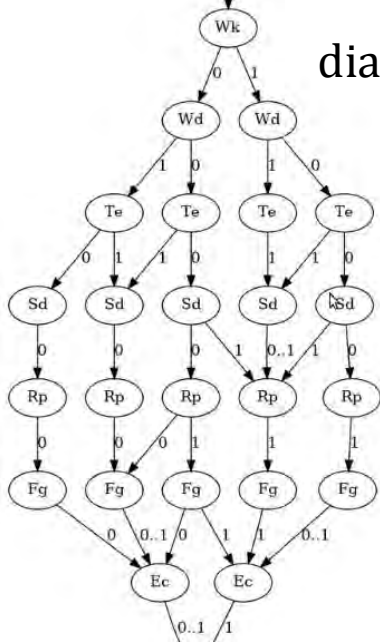

Shift to **symbolic** engines and (LTL / CTL)

temporal logics for the analysis *Contingent*
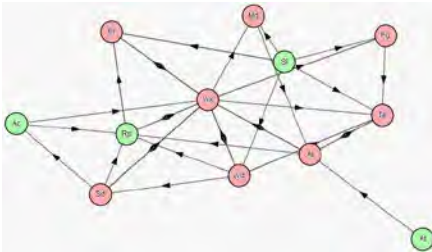
Decision diagram

Always / Sometimes true

Temporal logic formulae

*From now on, will this community **always reach** the **possibility** to have a **stable** maximally rich assemblage ?*

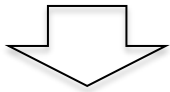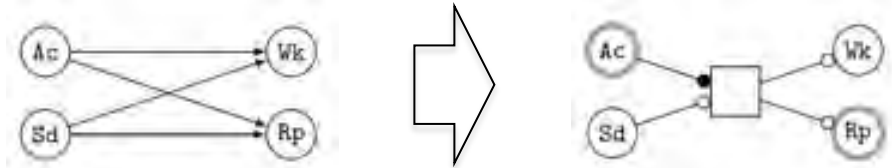$$\varphi = \forall\mathbf{F}\ (\exists\mathbf{G}(maximal\ species\ richness))$$

Thomas et al. In prep.

Powerful, yet not sufficient → need in complementary (static) methods
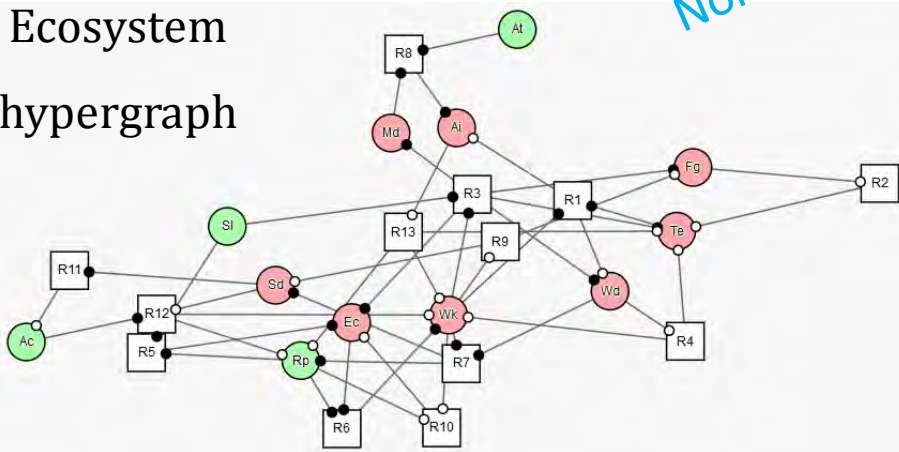
Chronology *(since 2020...)*

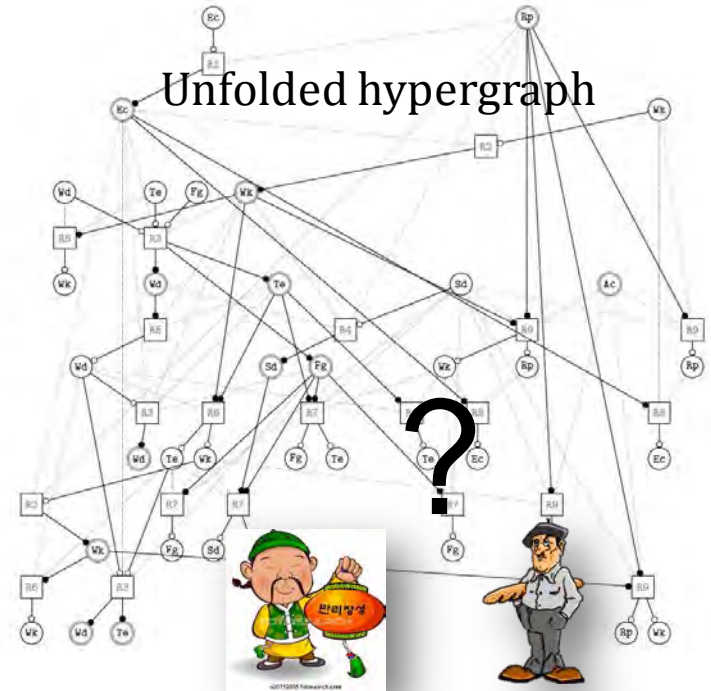A rigorous ecosystem **hypergraph** already formalized

Ecosystem hypergraph

Non Contingent

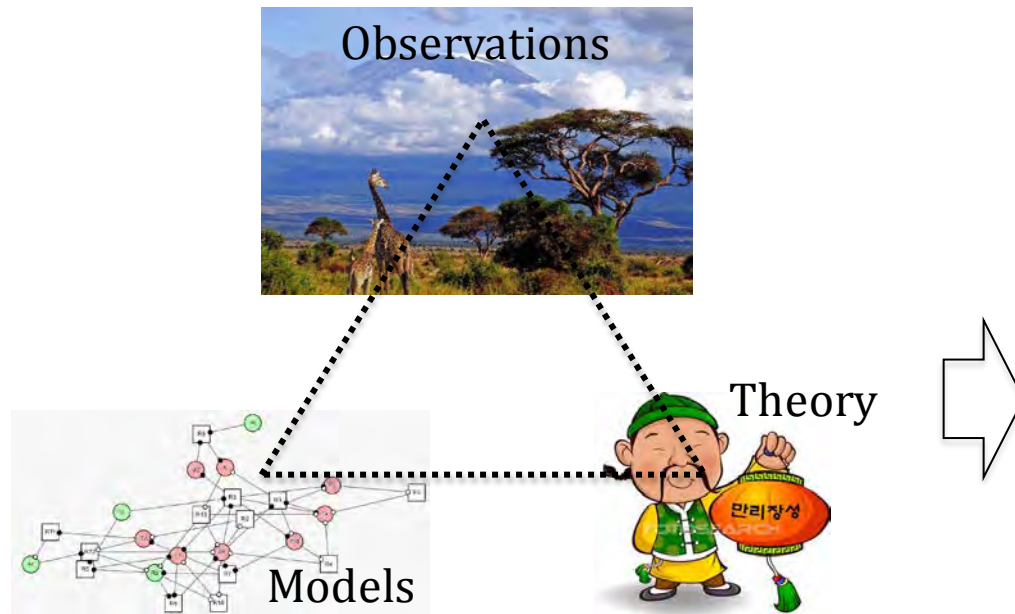Unfolded hypergraph

?

+ Most permissive semantics...

Analyzing methods to look for **invariants** in (unfolded) hypergraphs

Perspectives

Objectives:

- to study contrasted situations (observations)

- to develop more powerful tools (methods)

- to characterize language properties (theory)

The Languages of Nature

When Nature Writes to Itself

Observations

Theory

Models

Cédric Gaucherel

Cédric Gaucherel

Still in progress…

Conclusions

Ecosystems are not stable, nor unstable!

- To solve **new** (ecological/societal) challenges,

- To work on **any** (socio-)ecosystem,

- With the appropriate **methods**,

- To better understand its functioning,

- And to try finding our place in it.

otherwise …